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The Timber Tie Beam: The Analysis of Spatial Framework Joint

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Summary

The popularity of timber buildings is increasing at the moment. Timber is used as a main material for constructions of buildings, bridges and towers. Especially halls or office buildings need a construction of roof made by tie beams. Using of steel fasteners is quick, cheap and secure solution of joints in timber frame construction. There was a requirement for visible tie beam. For this reason the special joints by nogs were created, to design aesthetical and secure construction. This work studies a spatial frame work of unique timber tie beams. Their construction is engineered by four beams in two mainstreams. The critical point in the construction is a spatial joint in the cross of the beams. Therefore the FEM models have been created. The FEM results are compared with a real load test, performed on a real timber model. That way, we were able to monitor the critical spatial joint.

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Keywords: wood; frame; timber building; girder; pin joint, FEM

1. Introduction

The aim of the project was to design a building using the minimum of steel fasteners. The joints in this construction were designed by beech nogs with diameter form 30 mm to 40 mm and are classified in timber class D30. These type of joints could to transfer tensile forces. Some joints are made by traditional timber joins like tenon or notches. These types of joints could to transfer only press forces, so the FEM model was designed as nonlinear.

Wood has been used as a construction material since time immemorial and thanks to this fact all of its features are known. At the same time it is one of the reasons why structural systems proven by tradition are still used today and wood is still a very popular material for designing the supporting structures of objects. Wood as a natural organic material belongs to renewable resources; its renewability is possible within 30-120 years, depending on its

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type. It is a solid material, with good heat and sound insulating properties and a positive effect on the mental balance of people, too [3].

Larch wood, which has very good strength characteristics, was used for the design of this building. Another really positive feature of larch wood is its high resistance to weathering. The wood was chosen in Europe, especially from certain areas of Poland and Ukraine.

2. Description of the Construction

The proposed object is formed of four Portakabins, each of which has a plan shape of a regular octagon with a side length of 3.7 m; individual cells have different heights. This paper discusses the first Portakabin, which has two floors with a total height of about 8.5 m. Based on the assumption of the largest burden, this part has become the prototype for other parts of the entire building.

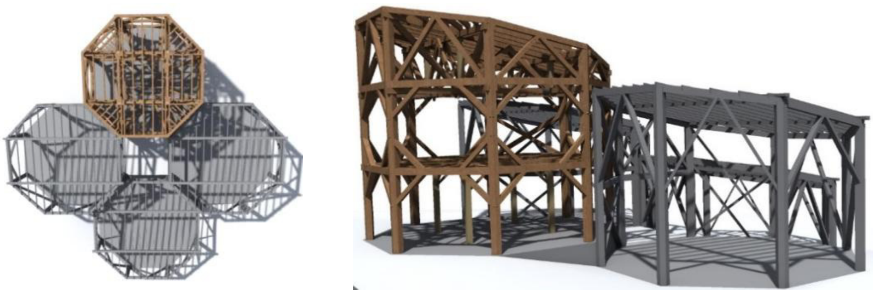

Fig. 1: Set of a heavy skeleton made of four Portakabins.

For getting internal forces, the FEM model, was created by using straight one dimensional elements combined with two dimension elements. Some timer members in construction couldn´t to transfer pressure stresses, so these elements are modelled with nonlinearity. The critical joints were modelled individually, see point 3, and final parameters, e.g. rigidity, and were inserted into general FEM model of the construction.

The supporting structure of the building is designed as a heavy skeleton with joints which do not use steel elements. Wood samples were tested by four-point bending test and by pressure test. In these tests the wood had compressive strength 25MPa and flexural strength 35MPa. Based on the mechanical destruction tests, the timber was placed in the C30 strength class (see. Fig.2) [2], [3]. Thanks to these strength tests it was possible to classify the wood and use it effectively in the structure.

Fig. 2: Implementation of the strength test on wooden samples.

Most of the construction is solved in articulated joints. The joints were designed as pin ones, using beech pegs of the D40 strength class or traditional craft joints. All joints are visible, and therefore high demands on their aesthetic appearance were emphasized. The construction had to be designed so that the wooden joints could transmit the resulting internal forces. The bearing capacity of the wooden dowels was based on tests conducted on the joints of historical buildings. [4].

2.1 Constructional Solution of the Object

Due to the requirement for a significant decrease in the number of steel fasteners, many unconventional constructional solutions of the object had to be used for the constructional design suggestion of this building. The first characteristic feature is the pillars and their exact pentagonal cross section (Fig. 3). The cross section was based on the ground plan of the object, a regular octagon.

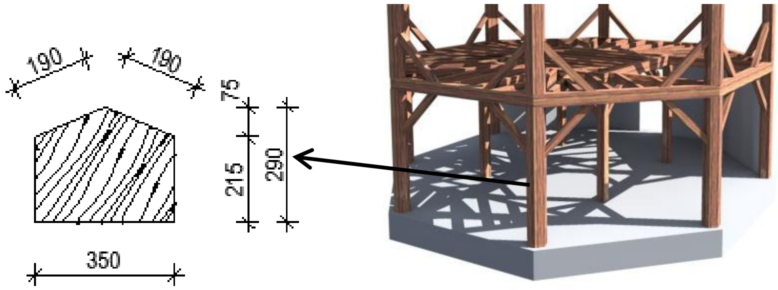

Fig. 3: Pillar and its ground plan.

The construction of the building has several specific solutions. One of them is the overall bracing system of the object, the supporting structure of the ceiling and the roof support system. With all these design measures, there was a significant increase in the stiffness of the whole structure. The biggest influence on spatial stiffness then has a spatial truss structure. The ceiling level stiffness is ensured by a coupled wood-concrete ceiling which follows the reinforced concrete walls in the level of the first floor. Spatial stiffness is largely supported by straps placed both at ceiling level and at floor level.

(a) (b)

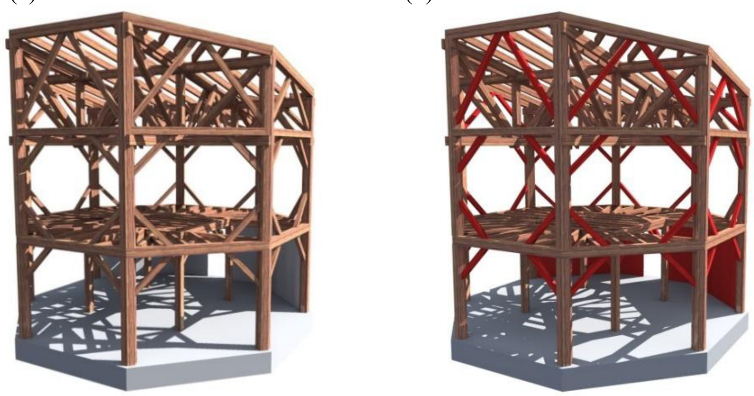

Fig. 4: (a) Supporting structure of the object (b) Designated stiffening elements.

The main supporting elements are massive columns of a pentagonal plan. On the columns on the first floor are simply stored circumferential ceiling girders, which form the supporting structure of the ceiling. The girders are designed with wooden rectangular sections. Trusses using pins are anchored to the pillars of the second floor.

To increase the vertical support stiffness strips were used. Due to the elimination of steel fasteners it was not possible to use these elements for tensile stress; they are therefore only designed for pressure transmission, as well as their connections with the main supporting elements. Another feature contributing to the stiffness are struts increasing spatial stiffness at the level of the roof truss.

The ceiling is designed as a composite timber-concrete structure. It was used due to a significant increase in carrying capacity and the overall stiffness of the ceiling. Another reason was to create a solid horizontal diaphragm at ceiling level.

3. Truss – Bearing Structure of the Roof

To ensure an open area without internal columns on the second floor, a roof using space truss was chosen. This design can be divided into two main directions. In one direction are used two identical counter trusses with the upper belts slope of 12 °. Pitched trusses have a structural height of 2900 mm at the highest point. Perpendicularly to these beams are placed two straight trusses of the construction heights of 1600 mm and 2300 mm. Because of the limited design lengths, the secondary elements in central fields are replaced and attached to the outer field using pin connections. The strips of the outer fields are formed by two sections so as to facilitate the installation of anchors to the support columns of the structure.

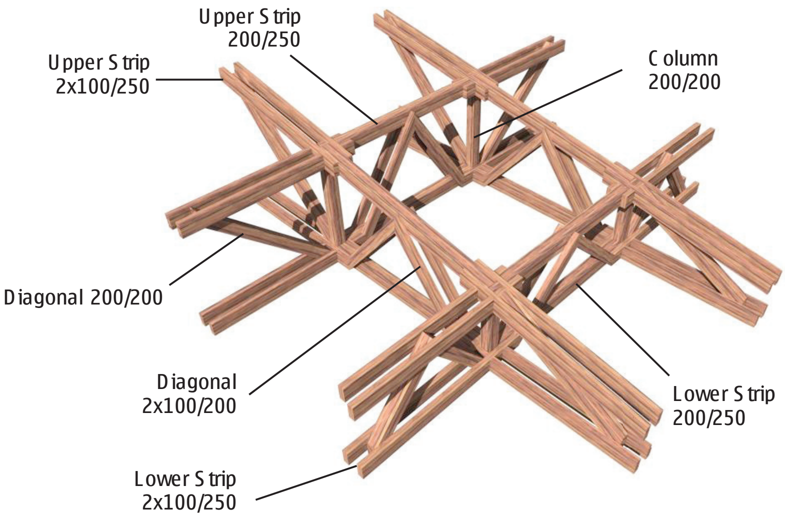

Fig. 5: Supporting roof construction.

3.1 Experimental Model of the FEM Truss Construction

The truss structure is structurally the most complex and demanding part of the building. To verify the correct model exposure of the finite element method the truss was first modelled as a single beam construction and then as a board structure, where the details were modelled by notches and pin connections according to the detail design. Both models were loaded by the force of 10kN in the location of critical joints and were subsequently compared as for the significant monitored variables, the deflection and reactions. [3].

The beam model was modelled axially using the real dimensions of structural elements. The actual position of the truss elements was taken into consideration. All joints were modelled as articulated, with the assignment of joint stiffness by calculating the k_{ser} slip module, by which the real stiffness of the joints was simulated.

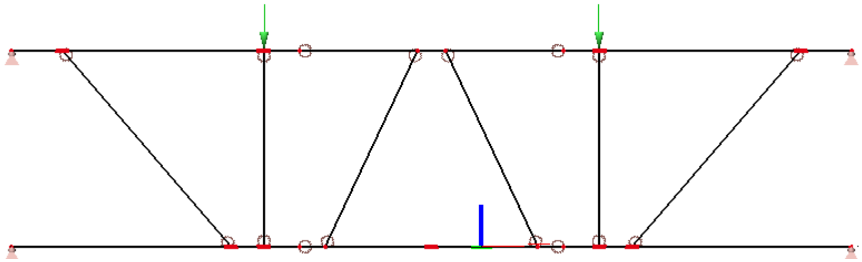

Fig. 6: FEM beam model.

The board model was modelled on a real parameter of the truss structure; the shape of the structural elements is modelled using wall elements on the actual thickness. In the first variant it is modelled without notches at the crossing point, in the second one then notches were already taken into account. Thanks to this measure it was possible to compare the influence of notches on stiffness of the structure. Pin connections were also realistically modelled in board models. The pins were modelled as rods with real cross section, length and material characteristics. For example rods were made from timber D30 with diameter 30 – 40mm and 200 mm length. These rods were attached to the wall elements by flexible joints with the k_{ser} rotational stiffness, calculated according to the CSN EN 1995-1-1 norm. The basic elements for the mashing of the construction were used four points members. By the pins the smaller triangle elements were used, therefore we got refined results of tension. Elements of the construction were meshed automatically. For both board models, a net of average size pieces of 25mm was used. In the areas of joints and the corners of notches, this net was thickened and refined to an average size of 5 mm pieces.

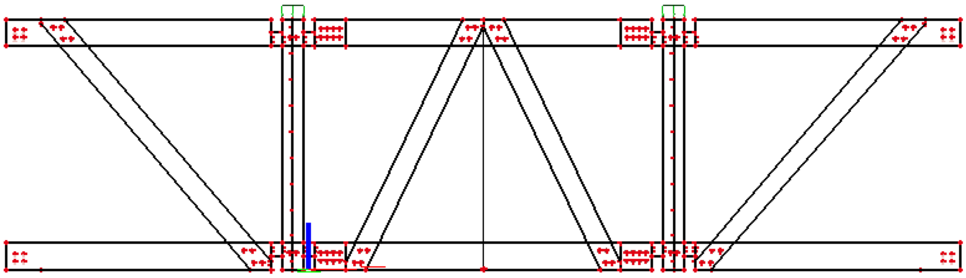

Fig. 7: FEM board model with notches.

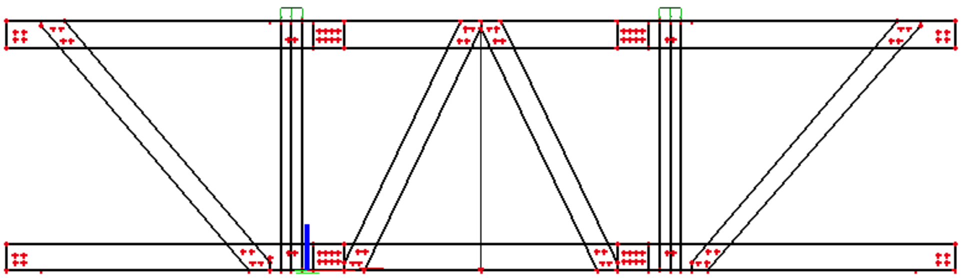

Fig. 8: FEM board model without notches.

In the next stage there will be a load test carried out on the real structure, whose results will be compared with the results gained from the FEM models.

3.2 Evaluation of the Results

Both kinds of the FEM model were compared for their behaviour as for the deformation of the structure. These were mainly a vertical deflection in the middle of the margin and the maximum shift which occurred at the site of splice of the truss belts in the central field. To check the correct functioning of the particular models the intensity of reactions was observed.

Table 1: Comparison of the results of the FEM models

Monitored variables	Central deflection u_z *(mm)*	Joints shift u_z *(mm)*	Stiffness *k (N.m^{-1})*
Beam model (Fig. 6)	3,0	3,2	6 666 666
Board model with notches (Fig. 7)	3,9	4,4	5 128 205
Board model without notches (Fig. 8)	3,8	4,4	5 263 158

The values listed in the Table 1 show the behaviour of the structure, depending on the FEM model used. In case of using the beam model, the most favourable values are the ones of constructional deformation. It is due to the fact that the model is not considered in terms of joint geometry. Comparing the actual board models, it is obvious that the influence of the notches on the overall stiffness of the structure is not too large. The risk of notches is therefore related to the actual assessment of the tensions in the given location. [1].

The stiffness of the truss was calculated as the ratio of load and deflection at the centre according to (1). Comparing the resulting stiffness of the FEM model shows that the beam pattern is stiffest. The resulting stiffness of lattice models is evident according to Table1.

$$k = \frac{\sum F}{u_z} = [N \cdot m^{-1}] \tag{1}$$

The rotational stiffness of the particular joints and pins was given by the k_{ser} module slip (2). The pin-slip module was calculated according to the applicable European standards of CSN EN 1995-1-1 and it differed according to the sections of the pins. The FEM beam model was also assigned particular stiffness depending on the number of mechanical fasteners at the joints. [4].

$$k_{ser} = {\rho_m}^{1,5} d/23 = [N \cdot mm] \tag{2}$$

4. Suggestion for Crossing

The most critical and also structurally the most interesting design detail in the structure is the crossing point of lower and upper belts trusses. In this joint there is a crossing of elements in three directions. To achieve the same level crossing of the beam axes, these beams were given notches halfway through the profile.

Thanks to the intersection the node does no longer act as a hinge joint, but there are negative bending moments which can be compared to the case of restraints. Besides these bending moments there are also additional moments in the joint due to the eccentricity of the neutral axis of the notch. Such eccentricity was then affected by normal forces, which triggered parasitic bending moments. The connection was designed for axial forces, for all of the bending moments and shear force, which is transmitted in the vertical joints. All the pin connections and weakened sections were also examined. The assessment of the joints was evaluated according to the applicable CSN EN 1995-1-1 standards. Within the calculation which was performed on the basis of a 3D beam joint model, the joint was designed to the use of 87%. [6].

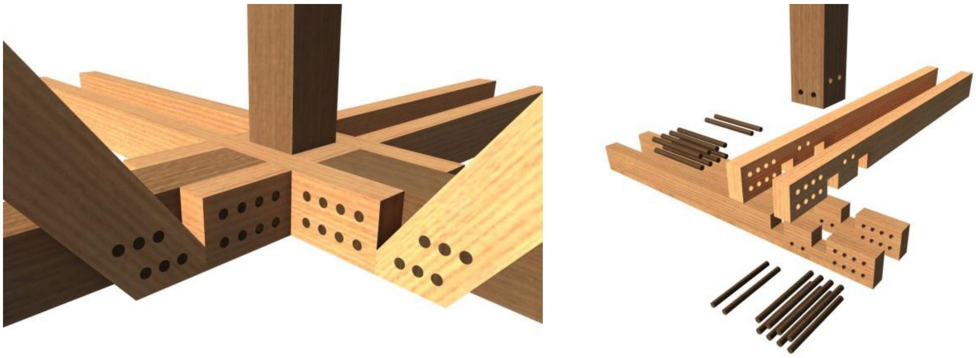

Fig. 9: Joint visualization at crossing point.

In the case of the experimental FEM plate model there is under the load of 10kN per node, as shown in Fig. 7, at the critical point reached normal compressive stress of nearly 8 MPa, tensile normal stress is then 9 MPa, with the critical characteristic value of strength being 18 MPa. In the case of experimental load the critical notch point is used for around 50%.

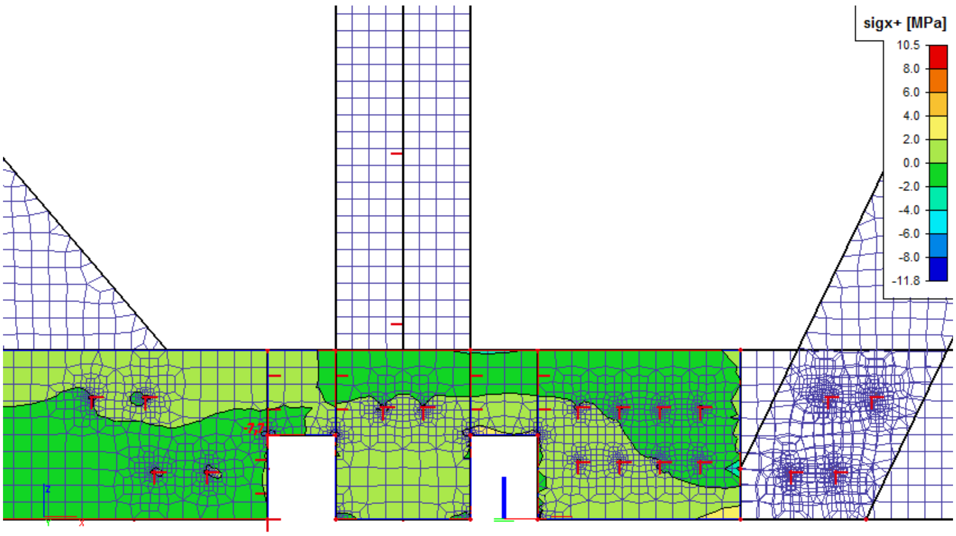

Fig. 10: Distribution of normal stress at a critical point of connection.

With some elements dry cracks appeared at the place of notches. This phenomenon significantly decreased the wood strength; particularly the pin joint strength was significantly reduced, since the pins in the holes did not physically take part in the transmission of internal forces. The negative effects of this phenomenon can be eliminated by choosing the right wood for the production of structural elements. An extreme option is then to fill in the cracks with PU based adhesive and the subsequent profile fastening. [2], [5].

Fig. 11: The picture of dry crack at the place of pin join.

5. Conclusion

Wood as a construction material is again gaining popularity for the construction of buildings. It is largely due to its strength characteristics, renewability, energy use, thermal and acoustic insulation properties, and its beneficial effect on the human psyche. The use of wood did not stop at traditional construction carpentry, but it is increasingly being used for the construction of new types of structures. The hereby described structure is one of them.

To compare the results FEM models were created. In most cases it is sufficient to use the beam model for designing. Although the stiffness of the joint calculated according to the CSN EN 1995-1-1 norm was taken into account with the beam model, the stiffness of the beam model was higher. Creating and refining the plate model led to taking into account the geometry of dowel joints, the rotational stiffness of pins and notches, thus reducing the stiffness of the truss and increasing deformation.

In practical design and assessment of current cases of wooden structures a beam FEM model of the structure is sufficient. In the case of development and testing of new structural systems, it is recommended to create an accurate model of the structure and critical points and thus all the factors affecting the stiffness of the structure and its deformation were taken into account.

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